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Determination of the ratio of b-quark fragmentation fractions f_s/f_d in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector

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Abstract

With an integrated luminosity of 2.47 fb^{-1} recorded by the ATLAS experiment at the LHC, the exclusive decays $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ of B mesons produced in pp collisions at $\sqrt{s}$ = 7 TeV are used to determine the ratio of fragmentation fractions f_s/f_d. From the observed $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ yields, the quantity $\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0\to J/\psi\phi)}{\mathcal{B}(B_d^0\to J/\psi K^{*0})}$ is measured to be 0.199 ± 0.004(stat) ± 0.008(sys). Using a recent theory prediction for $\frac{\mathcal{B}(B_s^0\to J/\psi\phi)}{\mathcal{B}(B_d^0\to J/\psi K^{*0})}$ yields $\frac{f_s}{f_d}$ = 0.240 ± 0.004(stat) ± 0.010(sys) ± 0.017(th). This result is based on a new approach that provides a significant improvement of the world average.

The production rate of B_s^0 (B_d^0) mesons is a product of the $b\bar{b}$ cross section, the instantaneous luminosity and the probability that the $\bar{b}$-quark is bound to an s-(d-) quark. The latter, denoted by the fragmentation fraction f_s (f_d), depends on the probability that in pQCD-inspired calculations [1, 2] a soft gluon splits into $s\bar{s}$ ($d\bar{d}$) and that the overlap of the $\bar{b}$ and s (d) wave functions is sufficiently large to produce a B_s^0 (B_d^0) bound state. In a similar fashion, B^+ mesons, B_c mesons and b-baryons are produced at the LHC with respective fragmentation fractions f_u, f_c and f_{baryon}. The fragmentation fractions are about 40% each for u- and d-quarks, 10% for s-quarks, at the percent level for c-quarks and $\sim 8\%$ for baryon production satisfying the constraint $f_u + f_d + f_s + f_c + f_{\text{baryon}} = 1$. Precise knowledge of the fragmentation fractions is essential for measuring b-hadron cross sections and branching fractions at the LHC. In particular for rare decays, such as the branching fraction measurement of $B_s^0 \to \mu^+\mu^-$ [3–5], a precise knowledge of f_s/f_d is important since it improves the sensitivity of searches for new physics processes beyond the Standard Model (SM). The fragmentation ratio f_s/f_d is a universal quantity that was measured by LEP experiments [6], CDF [7] and LHCb [8, 9]. This Letter presents a measurement of f_s/f_d using $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ decays.

The ratio of fragmentation fractions f_s/f_d is extracted from the measured $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ signal yields, $N_{B_s^0}$ and $N_{B_d^0}$. These are converted into B_s^0 and B_d^0 meson yields after dividing by the branching fractions of the relevant decays and correcting for the relative efficiency $\mathcal{R}_{\text{eff}}$ that is expressed as a product of acceptance and selection efficiency ratios for the two modes and is determined from Monte Carlo (MC) simulations:

$$\frac{f_s}{f_d} = \frac{N_{B_s^0}}{N_{B_d^0}} \frac{\mathcal{B}(B_d^0 \to J/\psi K^{*0})}{\mathcal{B}(B_s^0 \to J/\psi\phi)} \frac{\mathcal{B}(K^{*0} \to K^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)} \mathcal{R}_{\text{eff}}, \tag{1}$$

where the J/ψ, ϕ and K^{*0} are reconstructed in their $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$ and $K^{*0} \to K^+\pi^-$ final states [10], respectively. The data sample consists of pp collisions collected with the ATLAS detector at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 2.47 ± 0.04 fb^{-1}. The ATLAS multipurpose detector is described in detail in Ref. [11].

The PYTHIA 6 and 8 [12, 13] MC generators with parameters tuned to reproduce ATLAS data [14] are used to simulate background and signal events, respectively. For the signal channels, the angular distributions are produced with the measured polarization parameters [15]. The detector response for the generated events is simulated with GEANT4 [16, 17].

The $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ signal candidates consist of two muons and two hadrons originating from a common secondary vertex. The J/ψ candidates are selected from the dimuon trigger sample requiring two oppositely charged muon candidates, each having a transverse momentum of $p_T > 4$ GeV. Reconstructed muon candidates are categorized either as combined or segment-tagged muons. A combined muon consists of an inner detector (ID) track combined with a muon spectrometer (MS) track using tight matching criteria, while a segment-tagged muon requires an ID track and track segments in the MS that are not reconstructed as an MS track [11]. The two muons, of which at least one must be a combined muon, are fitted to originate from the same two-track vertex. The vertex fit chi-square per degree of freedom (dof) is required to be $\chi^2/\text{dof} < 10$. To improve the sample purity, each muon track must have at least one hit in the pixel detector, more than five hits in the silicon strip detector and at least one hit in the transition radiation tracker that reduces the pseudorapidity coverage to $|\eta| < 2.0$ [18].

Since the dimuon mass resolution is different for muons reconstructed in the endcaps ($1.05 < |\eta| < 2.5$) and for muons reconstructed in the barrel ($|\eta| < 1.05$), all accepted J/ψ candidates are divided into three

classes: two barrel muons (BB), one endcap and one barrel muon (EB), and two endcap muons (EE). The parameters describing the dimuon mass distribution in the J/ψ signal region for the three pseudorapidity classes in data and in $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ MC signal samples are extracted from maximum-likelihood fits. Signal events are selected requiring mass windows of $\pm 3\sigma$ around the J/ψ peak in data and simulations. For data, the selected signal regions are 2.991–3.197 GeV for BB, 2.955–3.235 GeV for EB and 2.914–3.275 GeV for EE classes, while in simulations they are slightly smaller.

The B_s^0 candidates are reconstructed from a J/ψ candidate plus two oppositely-charged hadrons with a kaon mass hypothesis assigned. The dimuon mass is constrained to the J/ψ mass [15] and the J/ψ and two kaons have to originate from the same vertex. All combinations are accepted if $p_{\mathrm{T}}(B_s^0) > 8$ GeV, $\chi^2/\mathrm{dof} < 3$ for the vertex fit and the K^+K^- invariant mass lies in the range determined by ± 2 natural widths (Γ_ϕ) around the ϕ mass peak, $1011 < m_{K^+K^-} < 1028$ MeV. The $m_{K^+K^-}$ distribution is modeled with a Breit-Wigner line shape convolved with a Crystal Ball function [19]. The selected mass window retains 85% of signal events.

The B_d^0 candidates are reconstructed in a similar way. Here, one track of the K^{*0} decay is assigned a kaon mass hypothesis and the other track a pion mass hypothesis. Since ATLAS has limited kaon-pion separation capability in the momentum range relevant for this analysis, both $K\pi$ mass assignment combinations are tested. That with mass closest to the nominal K^{*0} mass is chosen yielding the correct $K\pi$ selection for 86% of all K^{*0} candidates. The probability density function (PDF) for the invariant mass of correctly selected $K\pi$ candidates is modeled with a relativistic Breit-Wigner line shape convolved with a Crystal Ball function, while that where the K and π are swapped is modeled with a Gaussian function. The decay $B_s^0 \to J/\psi\phi$ produces a peaking background in $B_d^0 \to J/\psi K^{*0}$ that appears in the low K^{*0} mass region. To remove this contribution, the selected K^{*0} region is constrained to one K^{*0} decay width around the K^{*0} mass peak, corresponding to $847 < m_{K\pi} < 942$ MeV for data. Since the K^{*0} line shape is narrower in the MC simulations than in data, the $K\pi$ mass selection needs to be adjusted in simulations to produce identical efficiencies in data and simulations. For the K^+K^- mass selection, a similar procedure is used.

The signal-to-background ratios for $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ decays are optimized using three variables with high background suppression power: the χ^2/dof of the B vertex fit, the transverse decay length L_{xy} defined as the length of the vector from the primary vertex (PV) [20] to the B decay vertex in the transverse plane, and the pointing angle α defined as the angle between the B meson transverse momentum and L_{xy}. If more than one PV candidate exists, the one is selected for which the sum of squared transverse momenta of all tracks originating from the vertex, $\sum p_{\mathrm{T}}^2$, yields the highest value. The χ^2/dof, L_{xy} and α selection criteria are optimized using simulated $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ events for signal and data sidebands for background.

To produce similar p_{T} and η distributions in data and MC, data-driven weights are obtained by the following procedure. Sideband-subtracted $B_s^0 \to J/\psi\phi$ ($B_d^0 \to J/\psi K^{*0}$) p_{T} and η distributions from data are compared with corresponding distributions in simulation in the signal region, $5.32 < m_{J/\psi\phi} < 5.42$ ($5.21 < m_{J/\psi K^{*0}} < 5.35$) GeV. The upper and lower sidebands $5.20 < m_{J/\psi\phi} < 5.25$ ($5.09 < m_{J/\psi K^{*0}} < 5.16$) GeV and $5.48 < m_{J/\psi\phi} < 5.53$ ($5.40 < m_{J/\psi K^{*0}} < 5.47$) GeV are selected such that their summed yields represent the expected backgrounds in the signal region for the data. The weights are obtained by dividing the yield in each p_{T} and η bin in data by the corresponding yield of the MC sample using only events with odd event numbers. Thus, for each bin (i) and (j) of the p_{T} and η distributions, a

weight is determined as a product of a p_{T}-dependent and η-dependent weights:

$$W_{ij}(p_{\mathrm{T}}, \eta) = \frac{n_i^{\mathrm{data}}(p_{\mathrm{T}})}{n_i^{\mathrm{MC}}(p_{\mathrm{T}})} \times \frac{n_j^{\mathrm{data}}(\eta)}{n_j^{\mathrm{MC}}(\eta)}, \tag{2}$$

where $n_i^{\mathrm{data/MC}}(p_{\mathrm{T}})$ is the normalized number of entries in the p_{T} bin i and $n_j^{\mathrm{data/MC}}(\eta)$ is that in the η bin j. To obtain good agreement between data and simulation, the procedure is repeated twice. The two sets of weights are multiplied and are used to correct the p_{T} and η distributions of the MC sample with even event numbers. From the corrected MC samples, distributions for χ^2/dof, L_{xy} and α are determined that are in good agreement with those measured in the data. The correlation between p_{T} and η is small and is accounted for in the systematic error.

For both modes, the dominant background originates from a J/ψ produced at the PV plus two oppositely charged hadrons (direct J/ψ) [21]. Since the hadrons are not associated with any B_s^0 (B_d^0) decay, the $J/\psi K^+K^-$ ($J/\psi K^+\pi^-$) invariant-mass spectrum does not peak but decreases with mass. Another large background consists of two random low-momentum, oppositely charged muons combined with two random charged hadrons. Here, the dimuon mass distribution does not peak at the J/ψ nor does the four-particle mass show any peaking structure. Inclusive decays $B \to J/\psi X$ where X is a single hadron or a collection of hadrons provide a source of background that is very similar to the signal. If X consists of exactly two charged-particle tracks (without any π^0), the mode is topologically indistinguishable from the signal mode. Self-cross-feed in which one or both hadrons from the ϕ (K^{*0}) decay are replaced with random hadrons is negligible. In addition, peaking backgrounds from $B_d^0 \to J/\psi K^{*0}$ and $B_d^0 \to J/\psi K^+\pi^-$ contribute to $B_s^0 \to J/\psi\phi$ while $B_d^0 \to J/\psi K^+\pi^-$ also contributes to $B_d^0 \to J/\psi K^{*0}$.

To reduce these backgrounds, the χ^2/dof, L_{xy} and α selections are optimized for each mode separately by determining the maximum value of $S/\sqrt{S+B}$ as a function of selected values for the observable to be optimized, where S represents the signal yield obtained from simulation and B is the background extracted from data sidebands. For the B_s^0 (B_d^0) mode, the optimization yields $\chi^2/\mathrm{dof} < 2.4$ (2.6), $L_{xy} > 0.26$ (0.30) mm and $\alpha < 0.14$ (0.12) rad. In combination with the J/ψ mass requirement, the χ^2/dof selection reduces the combinatorial background significantly, while the L_{xy} and α selections remove most of the direct J/ψ background.

In the final sample, the signal yields $N_{B_s^0}$ and $N_{B_d^0}$ are extracted from unbinned extended maximum-likelihood fits to the $J/\psi K^+K^-$ and $J/\psi K^+\pi^-$ invariant-mass spectra, respectively. The B_s^0 signal PDF is modeled with three Gaussian functions with common mean that is determined from the fit while widths and fractions are fixed to the values obtained from MC simulations. To account for possible width differences in the two narrowest Gaussian functions between data and simulation, an additional scale factor is introduced, which is left free in the fit. The peaking background PDF is modeled with a Crystal Ball function with parameters fixed to the values obtained in simulations. The peaking background yield of 652 ± 93 events is calculated from the B_d^0 signal yield. The selection efficiencies of both peaking background modes are determined from simulation and are fixed in the fit to data. The remaining residual backgrounds are modeled with an exponential function leaving fraction and exponent free in the fit to data.

The B_d^0 signal PDF is parametrized with three Gaussian functions that describe both the correctly reconstructed and swapped $K^+\pi^-$ events. The PDF of the peaking background is modeled with a sum of Crystal Ball and Gaussian functions for which the relative $B_d^0 \to J/\psi K^+\pi^-$ yield with respect to that of the

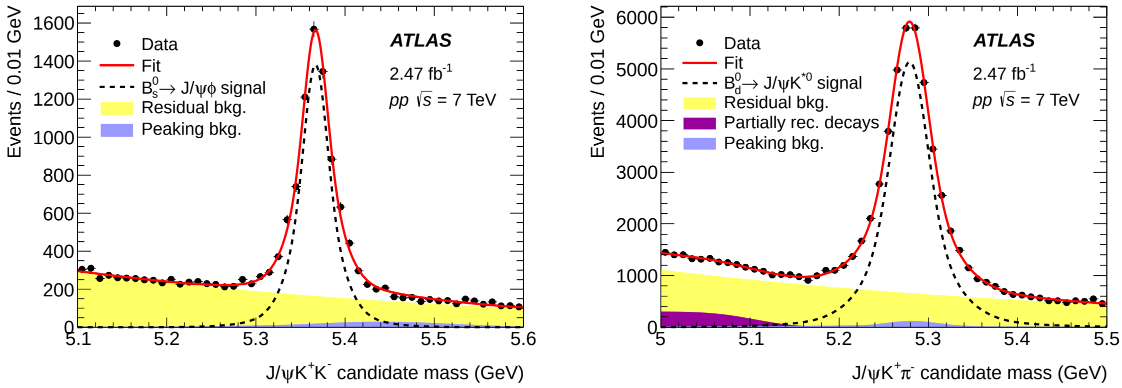

Figure 1: The invariant-mass spectra of $B_s^0 \to J/\psi\phi$ (left) and $B_d^0 \to J/\psi K^{*0}$ decays (right) for data (points with error bars), total fit (solid), signal (dashed), residual background (yellow shaded), partially reconstructed events (magenta shaded) and peaking background (blue shaded).

$B_d^0 \to J/\psi K^{*0}$ signal is determined from the corresponding branching fractions and selection efficiencies, yielding (4.7 ± 2.4)%. Most of the residual background is modeled with an exponential function while partially reconstructed $B \to J/\psi X$ decays require parameterization with a complementary error function. All parameters of the residual background PDFs are left free in the fit.

Figure 1 shows the measured $J/\psi\phi$ and $J/\psi K^{*0}$ invariant-mass spectra with fits overlaid. The fits yield $N_{B_s^0} = 6640 \pm 100$ $B_s^0 \to J/\psi\phi$ and $N_{B_d^0} = 36290 \pm 320$ $B_d^0 \to J/\psi K^{*0}$ signal events. The χ^2/dof values of the fits are 0.959 for B_s^0 and 0.945 for B_d^0 indicating that both fits describe the data well.

The additive systematic uncertainties result from the $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ signal and background parameterizations. The contribution from the signal shape parameterization is calculated by varying the five fixed parameters within $\pm 1\sigma$ in a multivariate Gaussian function that takes into account all correlations. For non-peaking backgrounds, the exponential function is replaced with a second-order polynomial for the B_s^0 and with a second-order polynomial plus an error function for the B_d^0. The difference in signal yield with respect to the nominal fit is taken as a systematic error. For peaking backgrounds, the fixed parameters are varied by $\pm 1\sigma$ and the difference with respect to the nominal yield is taken as a systematic error. In addition, since S-wave contributions from $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi f_0(980)$ decays to $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ are neglected in the fits, an uncertainty is derived using the ATLAS measured contribution of 2.4% [22] for $B_s^0 \to J/\psi\phi$, and the contribution of 1% for $B_d^0 \to J/\psi K^{*0}$ derived from the MC simulation. All additive systematic errors are added in quadrature, yielding total additive uncertainties of 220 $N_{B_s^0}$ and 650 $N_{B_d^0}$ events.

The multiplicative systematic uncertainty includes contributions from the relative efficiency and the branching fractions of the ϕ and K^{*0} decays. The uncertainty on the relative efficiency is dominated by the uncertainty on the ϕ/K^{*0} selection (1.2%) which is obtained by varying the fixed fit parameters in the ϕ and K^{*0} fits by $\pm 1\sigma$ and adding all contributions in quadrature. Other uncertainties from the J/ψ selection (0.2%), reweighting (0.4%), B_s^0 and B_d^0 lifetimes (0.002%) and the contribution due to uncertainties in the polarization parameters (0.01%) are negligible. Varying the selection criteria of χ^2/dof, L_{xy}, and α gives negligible contributions. Table 1 summarizes the contributions of the additive and multiplicative systematic errors.

Table 1: Measured B_s^0 and B_d^0 signal yields, the efficiency ratio $\mathcal{R}_{\text{eff}}$ extracted from simulations, world averages for ϕ and K^{*0} decay branching fractions as well as corresponding systematic uncertainties σ on $\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0\to J/\psi\phi)}{\mathcal{B}(B_d^0\to J/\psi K^{*0})}$.

Observable	Value	σ	Ref.
$N_{B_s^0}$	$6640 \pm 100 \pm 220$	3.3%	
$N_{B_d^0}$	$36290 \pm 320 \pm 650$	1.8%	
$\mathcal{R}_{\text{eff}}$	$0.799 \pm 0.001 \pm 0.010$	1.3%	
$\mathcal{B}(\phi \to K^+K^-)$	0.489 ± 0.005	1.0%	[15]
$\mathcal{B}(K^{*0} \to K^+\pi^-)$	0.66503 ± 0.00014	0.02%	[15]
Total		4.1%	

From the ratio $N_{B_s^0}/N_{B_d^0}$ after efficiency correction and division by ϕ and K^{*0} decay branching fractions, ATLAS measures

$$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0 \to J/\psi\phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})} = 0.199 \pm 0.004(\text{stat}) \pm 0.008(\text{sys}). \tag{3}$$

A perturbative QCD prediction [23] yields

$$\frac{\mathcal{B}(B_s^0 \to J/\psi\phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})} = 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c),$$

where the uncertainties result from the shape parameter ω_B of the B meson wave function, meson decay constants f_M, Gegenbauer moments a_i in the wave functions of the light vector mesons and the c-quark mass. Adding all contributions linearly yields a 7.1% theory error. Using this prediction, the ratio of fragmentation fractions is measured to be

$$\frac{f_s}{f_d} = 0.240 \pm 0.004(\text{stat}) \pm 0.010(\text{sys}) \pm 0.017(\text{th}). \tag{4}$$

Figure 2 (right) shows the ATLAS f_s/f_d measurement in comparison with results from LEP [6], CDF [6, 7] and LHCb [8, 9]. The ratio f_s/f_d may depend on p_{T} and η of the B meson, e.g. LHCb observes a p_{T} but no η dependence of f_s/f_d [8]. Figure 2 (left) shows the p_{T} dependence of f_s/f_d for ATLAS and that of other experiments. To investigate the p_{T} and η dependences of f_s/f_d, the data sample is divided into six p_{T} bins in the range 8 GeV $< p_{\mathrm{T}} <$ 50 GeV and into four η bins for $|\eta| < 2.5$ such that the number of events in each bin is approximately equal. The f_s/f_d distributions as a function of p_{T} and η have been fitted with a uniform (first-order polynomial) distribution yielding fit p-values 0.54 (0.66) and 0.66 (0.49), respectively. No significant f_s/f_d dependence on p_{T} and $|\eta|$ is seen at the present level of accuracy.

In summary, this Letter reports on the first ATLAS measurement of the ratio of $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ branching fractions multiplied by the ratio of fragmentation fractions f_s/f_d from which f_s/f_d is determined. The data were produced at the LHC in pp collisions at $\sqrt{s}$ = 7 TeV and correspond to an integrated luminosity of 2.47 fb^{-1}. This f_s/f_d measurement, obtained with a new approach, agrees with the LHCb [8, 9] results improving the world average considerably. A comparison with the CDF [6, 7] measurement and the LEP [6] average confirms the universality of f_s/f_d. The ATLAS data show no dependence on p_{T} nor on $|\eta|$ within the kinematic range tested.

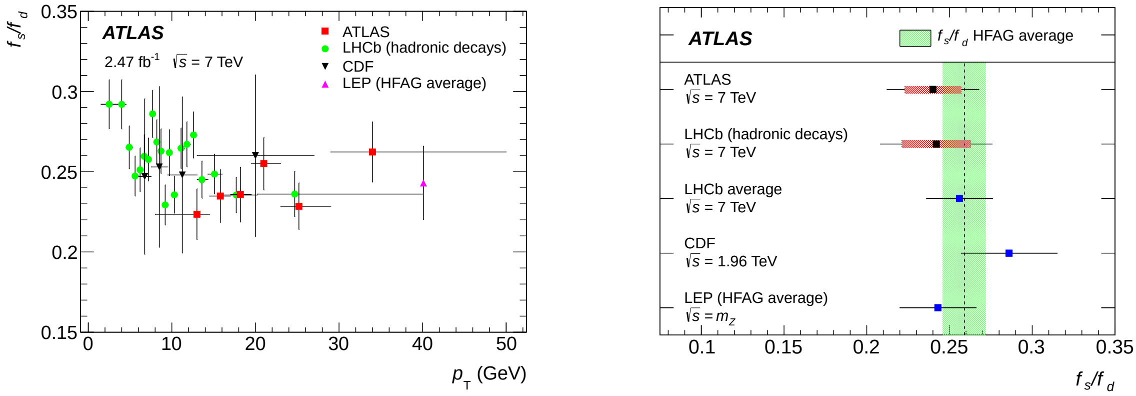

Figure 2: (Left) Measurements of f_s/f_d versus B meson p_T for CDF [7], LHCb [8] and ATLAS, where the ATLAS data points are plotted at the average p_T of the events in each bin. The error bars show statistical and systematic errors added in quadrature. The LEP ratio, taken from Ref. [6], is plotted at an average p_T value in Z decays. (Right) Measurements of f_s/f_d (black and blue points with error bars) from LEP [6], CDF [6], LHCb [8, 9] and ATLAS. The total experimental error (thin black) is added linearly to the theory error (thick red). The green-shaded region shows the HFAG average obtained using the blue points.

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